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CORRELATION OF STRUCTURE AND THERMAL CONDUCTIVITY OF HIGHLY DISPERSE POROUS-FIBER MATERIALS UNDER VARIATIONS OF TEMPERATURE AND MOISTURE

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The effect of the structure (pore type, pore size, fiber diameter) of highly disperse porous materials on their thermal conductivity is considered.

Contemporary technology makes it possible to use mineral and glass fibers of different length and thickness to produce fibrous materials of virtually any degree of dispersion. In principle, all these fibers can be used for heat-insulating materials in construction. However, micron-thin fiber (diameter $d < 0.6 \mu\text{m}$) is preferable for ultrafilters; ultrathin fiber ($d = 0.5 - 1.0 \mu\text{m}$) for glass paper, glass cardboard, and adsorbents; superthin fiber ($d = 1 - 3 \mu\text{m}$) for superlight heat-insulating and sound-absorbing articles and insulation for equipment operating at high temperatures; thin ($d = 4 - 12 \mu\text{m}$) for heat-insulating and acoustic technical or constructional parts; thick ($d = 13 - 15 \mu\text{m}$) for heat and sound insulation in construction and for reinforcement of waterproof materials and fiber glass; coarse ($d = 25 \mu\text{m}$) for concrete reinforcement. Superthin and thin fibers are used to obtain different heat-insulating products: sewn mats and plates of various density and stiffness with a binder.

The content of the components and their properties and arrangement determine the material structure, which to a great extent determines the macroscopic parameters of heat-insulating articles. Porous-fiber materials contain three components: fiber, air, and a binder. The part by volume of these components in highly disperse systems with a density up to 100 kg/m^3 is, respectively: $m_1 \approx 0.04$, $m_2 \approx 0.95 - 0.96$, and $m_3 < 0.05$.

The parameter m_2 characterizes the porosity of the articles. The apparent density, or the volume mass of products ρ_0 , is determined from the expression

$$\rho_0 = m_1 \rho_f = (1 - m_2) \rho_f,$$

where ρ_f is the true density of the fiber; usually $\rho_f = 2500 - 2800 \text{ kg/m}^3$.

Theoretically, the thermal conductivity of material λ of any structure is within the following limits [1]:

$$\lambda_1 \frac{v}{(1 - m_2)v + m_2} \leq \lambda \leq \lambda_1(1 - m_2 + vm_2), \quad (1)$$

where v is the coefficient characterizing the ratio of thermal conductivity of air (gas) in pores λ_2 to the thermal conductivity of the skeleton (fiber) λ_1 .

The expression in the left part of inequality (1) represents the thermal conductivity of a laminar material whose layers are arranged perpendicularly to the heat flow (horizontal-laminar structure):

$$\lambda_{\perp} = \lambda_1 \frac{v}{(1 - m_2)v + m_2}.$$

The expression in the right part of inequality (1) represents the thermal conductivity of a laminar material whose layers are arranged parallel to the heat flow (vertical-laminar structure), i.e., the maximum possible thermal conductivity for prescribed porosity (density)

The thermal conductivity of materials with different structure can be estimated using a relatively simple expression [1, 2]:

$$\lambda = \lambda_1 \times \left\{ (1 - K)[(1 - m_2) + vm_2] + K \frac{v}{(1 - m_2)v + m_2} \right\}, \quad (2)$$

where K is the structural coefficient.

The analysis of the correlation between the thermal conductivity of variously structured materials and the thermal conductivity of the components integrating the system carried out in [1] and by the authors of the present paper made it

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possible to determine the value K for various structures (Table 1 and Fig. 1). Thus, the parameter K , which essentially characterizes the structural specifics of the materials, can be represented as a quantitative structural parameter. For instance, for fibrous materials with fibers mostly arranged perpendicular to the heat flow, $K = 0.80$.

Sources in the literature [4] offer certain data for determining the thermal conductivity of materials with different structures. Using Eq. (2), it is possible to determine the thermal conductivity for the respective K in the same way as in using the formulas from Table 1.

For the considered fiberglass articles at a temperature of 15°C , $\lambda_2 = 0.028 \text{ W}/(\text{m} \cdot \text{K})$, $\lambda_1 = 0.7 \text{ W}/(\text{m} \cdot \text{K})$, $v = 0.04$, and $m_2 = 0.96$, the thermal conductivity is within the interval $0.028 \leq \lambda \leq 0.005 \text{ W}/(\text{m} \cdot \text{K})$.

For fibrous structures (heat flow perpendicular to fibers), according to Eq. (2) neglecting the value $(1 - m_2)v$, we obtain

$$\lambda \approx 0.2\lambda_1 \left[1 - m_2(1 - v) + 4 \frac{v}{m_2} \right].$$

Taking into account the given values of λ_1 , v , and m_2 , the thermal conductivity is $0.036 \text{ W}/(\text{m} \cdot \text{K})$, which agrees well with experimental data.

The parameters λ_1 , λ_2 , and v significantly depend not only on the gas-filling volume but also on the service conditions: temperature, moisture, and blowing-through of heat insulation. The effect of porosity on thermal conductivity for fibrous materials becomes perceptible at $m_2 > 0.9$, since un-

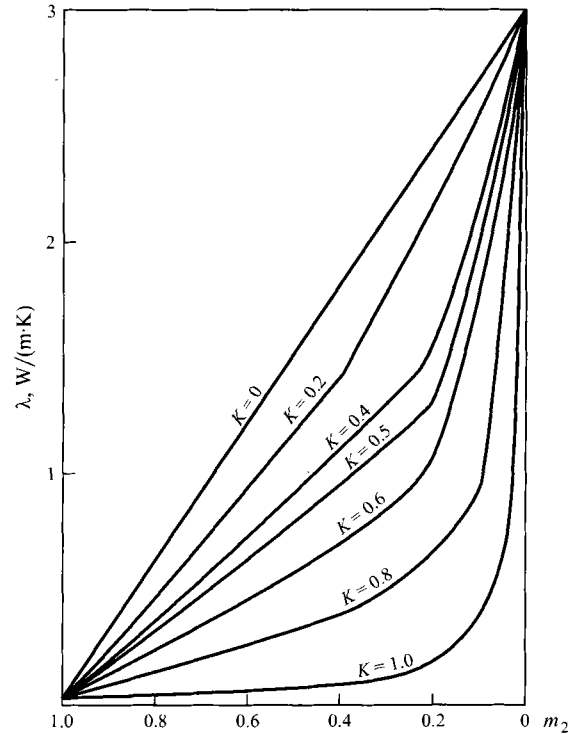


Fig. 1. Correlation of thermal conductivity of material λ and porosity m_2 .

der these conditions the pore size increases and the air convection in pores becomes stronger:

$$\lambda_2 = 0.022 + 40dm_2/(1 - m_2),$$

where d is the fiber diameter, m .

TABLE 1

Characteristics of model structure	Calculation formula	Structural coefficient	Reference
Vertical-laminar	$\lambda_1(1 - m_2 + vm_2)(1 - K)$	0	[1]
With mutually penetrating components (fibrous) splitting an elementary cell with planes parallel to heat flow (adiabatic splitting)	$\lambda_1 \left[m_2^2 v + (1 - m_2)^2 + 4v \frac{m_2(1 - m_2)}{1 + v} \right]$	0.18	[1]
Cubic-shaped inclusions (Odelevsky formula)	$\lambda_1 \left[1 - \frac{m_2}{\frac{1}{1 - v} - \frac{1 - m_2}{3}} \right]$	0.20	[3]
Spheroid inclusions (Khashin formula)	$\lambda_1 \left[\frac{1 - m_2 + (1 + m_2)v}{1 + m_2 + (1 - m_2)v} \right]$	0.45	[4]
With mutually penetrating components (fibrous) splitting an elementary cell with planes perpendicular to heat flow (isothermal splitting)	$\lambda_1 \left[m_2^2 v + (1 - m_2)^2 + \frac{4vm_2(1 - m_2)}{1 + v} \right]$	0.80	[1]
Limiting for sizes of the considered elements tending to zero (Lichtenecker formula)	$\lambda_1 \sqrt{v \frac{1 - m_2 + 1 + m_2 v}{(1 - m_2)v + m_2}}$	0.80	[5]
Horizontal-laminar	$K\lambda_1 \frac{v}{(1 - m_2)v + m_2}$	1.00	[1]

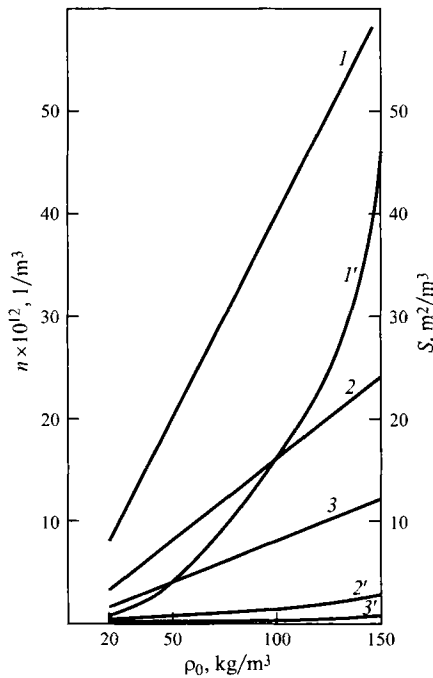


Fig. 2. Dependence of the number of contacts between fibers n ($1-3$) and the unit surface of fibers S ($1'-3'$) on fiber radius r and apparent density of material ρ_0 : $1-1'$) for $r = 2 \times 10^{-6}$ m; $2-2'$) for $r = 5 \times 10^{-6}$ m; $3-3'$) for $r = 10 \times 10^{-6}$ m.

Then

$$v = \left(0.022 + 40d \frac{m_2}{1-m_2} \right) / \lambda_1.$$

It is expedient to introduce this correction in the formula with the apparent density of heat-insulating materials below 80 kg/m^3 .

The thermal conductivity of heat-insulating materials largely depends on moisture. According to the data in [6], an increase by 1 vol. % in fiber-structured materials of density up to 150 kg/m^3 produces an increase in thermal conductivity by 8%. The hygroscopicity of fiberglass materials is low [7]: that of single fiber is 0.2% and that of sodium-calcium-silicate glass tissue is up to 3–4%. This is significantly less than the hygroscopicity of cotton (8%), wool (6%), peat plates of grade 200 (28%), and fibrolite of grade 300 (31%).

The surface area or, more exactly, the unit surface of the porous-fiber material has a significant effect on sorption, mass, and gas-transfer processes.

The overall surface area of the fibers S can be easily estimated in the following way:

$$S = 2\pi r l,$$

where r is the mean radius of the fibers, m, l is the total length of fibers per m^3 of the article, m/m^3 , and $\pi r^2 l \rho_f = \rho_0$.

Hence the unit surface per m^3 of the article is

$$S = 2\rho_0 / r\rho_f. \quad (3)$$

According to P. A. Rebinder's classification [8], there are the following types of bonds between moisture and material surface with different levels of bond energy: chemically, physicochemically (absorptionally), and physichomechanically (capillary) bonded water.

For example, in heat-insulating fiberglass articles, chemically bonded water can arise due to hydration of the glass surface. Adsorptionally bonded water, according to the analysis of the Brunauer, Emet, and Teller equation, forms a layer about 10^{-7} m thick on the surface of the fibers. Hence for $r = 5 \times 10^{-6}$ m, the water absorption due to adsorption is

$$W = \frac{S \times 10^{-7}}{\rho_0} 100 = \frac{2}{r\rho_f} 10^{-5} \approx 0.001 - 0.002\%.$$

Capillary moisture can only emerge on the site of fiber contacts, which explains the relatively low hygroscopicity of these materials and insignificant variations in their thermal conductivity in a highly moist atmosphere.

However, it should be noted that the situation changes completely if the structure does not prevent condensation of moisture vapor in the material (an especially direct moistening).

The order of magnitude of the number of contacts between the material fibers per m^3 of article, in the authors' opinion, can be determined from the expression

$$n = \left(\frac{\rho_0}{\pi\rho_f} \right)^2 \frac{1}{r^3}. \quad (4)$$

Figure 2 shows dependences (3) and (4) for $r = 2, 5$, and $10 \mu\text{m}$ and $\rho_0 = 20, 50, 100$, and 150 kg/m^3 .

Such a sharp increase in the unit surface and the number of contacts with increasing density of articles and decreasing fiber radius necessarily affects the behavior of the fibers when moistened. Thus, superthin fiber mats in moistening lose their heat-insulating properties and, moreover, their volume is significantly changed under the effect of capillary forces (they become condensed). After drying, the volume is not completely recovered. At the same time, it ought to be noted that articles made of mineral fibers are fast-drying [9]. Unlike finely porous hygroscopic heat-insulating materials such as perlite, mineral fiber articles which have larger gas-structural elements are characterized by a lower moisture-transfer potential. Therefore, when the moistened fibrous heat insulator contacts the surface of the surrounding structure, moisture from the heat-insulating material does not migrate into the wall, which ensure a satisfactory moisture state of the laminar structure.

Variations in service temperatures also affect the thermal conductivity of porous-fiber articles, which is especially important when they are used as fireproof materials. With increasing temperature, heat transfer by pores significantly changes (due to convection and radiation), and the thermal conductivity of the skeleton is modified.

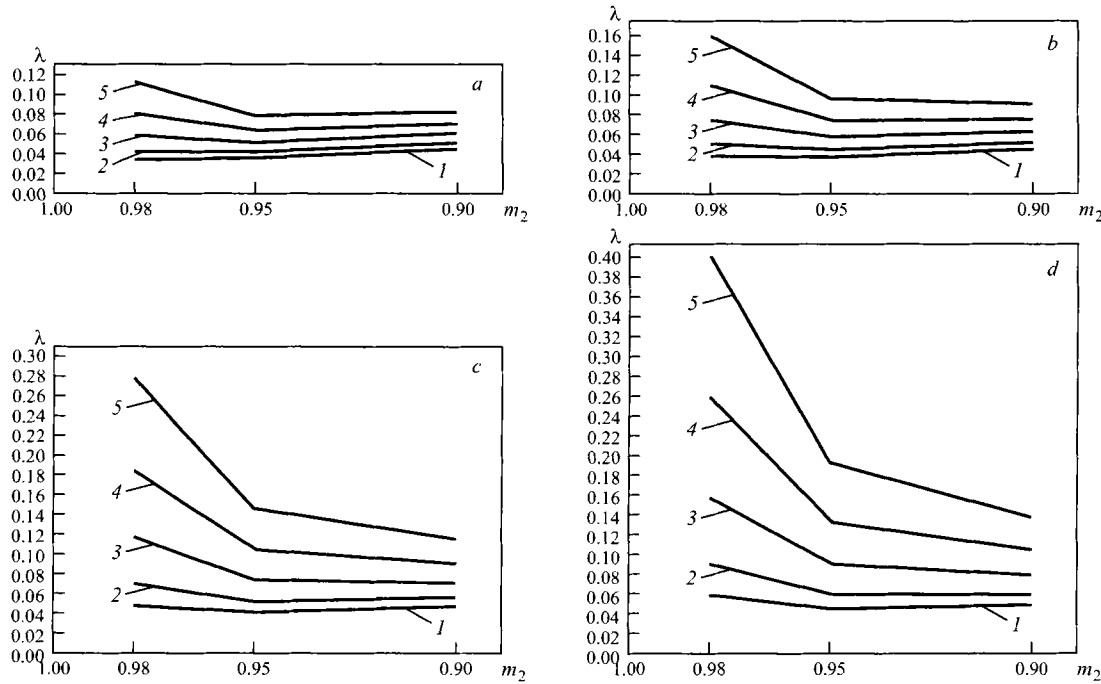


Fig. 3. Variation in thermal conductivity of fiber material depending on its porosity m_2 , fiber diameter d , and temperature t : *a*, *b*, *c*, and *d*) $d = 3, 5, 10$, and $15 \mu\text{m}$, respectively; 1, 2, 3, 4, and 5) 30, 100, 200, 300, and 400°C , respectively.

In the general case, the correlation of the thermal conductivity of gas in pores can be approximately expressed as a function [1]:

$$\lambda_r = \frac{\lambda_{r_0}}{1 + \frac{1}{T}} + 4\sigma\epsilon T^3\delta,$$

where λ_{r_0} is the thermal conductivity of gas in unlimited space for a certain initial pressure and temperature T [10]:

$$\lambda_{r_0} = \sqrt{\frac{3k}{MN_A}} \frac{C_m}{\sigma} \sqrt{T}; F_1 \text{ is the function depending on the}$$

accommodation coefficient; C_m is the molar heat capacity; σ is the effective collision section; ϵ is the degree of blackness of the pore walls; δ is the pore size; k is the Boltzman constant; M is the molecular mass of the gas; N_A is the Avogadro number.

Based on Kammerrer's experimental data obtained for materials with air-filled pores and taking $\epsilon = 0.7$, we can write

$$\lambda_r = \lambda_2 = \frac{128 \times 10^{-3} \sqrt{T}}{1 + \frac{13 \times 10^{-3}}{T\delta}} + 159 \times 10^{-8} \delta T^3.$$

With $T > 293 \text{ K}$, neglecting small values, we have

$$\lambda_2 = 128 \times 10^{-3} \sqrt{T} + 159 \times 10^{-8} \delta T^3. \quad (5)$$

The dependence of the thermal conductivity of fiber on temperature can be approximately expressed in the following way:

$$\lambda_1 = 0.7 + 1.6 \times 10^{-3} (T - 273). \quad (6)$$

By solving Eq. (2) together with dependences (5) and (6), the thermal conductivity can be determined for a wide temperature interval.

As a result of comparing estimated data with experimental ones, it was found that the effective diameter of pores is nearly an order of magnitude greater than the distance between fibers and can be estimated as follows:

$$\delta = 10(L - d) = 10 \left(\frac{d}{1 - m_2} - d \right) = 10d \frac{m_2}{1 - m_2}, \quad (7)$$

where L is the elementary cell length;

It is taken in this case that $d \approx (1 - m^2)$ [1].

Figure 3 shows the plots constructed based on Eqs. (2) and (5)–(7), which demonstrate the variations in thermal conductivity depending on external temperature. As was expected, the sharpest increase in thermal conductivity is observed in thick-fiber materials.

The dependences presented allow for preliminary estimation of the thermal conductivity in materials of different structures, for varying moisture and service temperatures.

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